Integrated Engineering

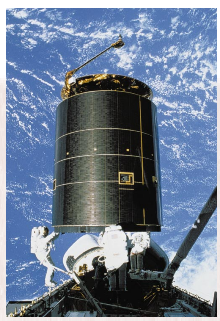
Extending NASA's Data Processing to Spacecraft

Marco A. Figueiredo, SGT
Patrick H. Stakem, Loyola College
Thomas P. Flatley and Tonjua M. Hines, NASA

Understanding the universe is a never-ending quest, and each discovery raises new questions. To acquire the data that will answer these questions, NASA is deploying increasingly complex scientific and environmental observation spacecraft. These platforms have, however, placed a growing burden on NASA's downlink assets, ground-based systems, and operating costs. Communications bandwidth and processing throughput already constrain scientific data gathering in both volume and rate. This limitation forces scientists to make hard choices between data collection priorities on one hand and bandwidth, processing, and archiving priorities on the other. The "Earth Observation System Data Product" sidebar gives an example of the complex phenomena about which NASA gathers data.

Over the past few decades, advances in ground-based processing and space-to-Earth links have fallen further behind NASA's requirements for handling observation data. Thus NASA's ability to observe and capture Earth phenomena of theoretical and practical interest far outstrips its ability to transfer, process, or store such data. Increasing the onboard computing power of spacecraft is one solution that may allow both space and ground-based systems to address these limitations.

Editors: Jerzy W. Rozenblit, University of Arizona, ECE 320E, Tucson, AZ 85721; jr@ece.arizona.edu; and Sanjaya Kumar, Honeywell Technology Center, MS MN65-2200, 3660 Technology Dr., Minneapolis, MN 55418; skumar@htc.honeywell.com



To keep pace with a flood of observation data, NASA plans to off-load many processing tasks to its spacecraft, which will pose interesting integration problems.

ONBOARD DATA PROCESSING

Traditional spacecraft architectures only collect, package, and transmit the data acquired by multiple onboard instruments. To date, the huge, high-performance computing systems needed to convert the spacecraft's instrumentation data into meaningful information have remained on the ground. We expect that spacecraft will need nothing less than supercomputing technology to perform meaningful onboard information processing.

Moving supercomputing power onto a spacecraft will require an integrated data architecture in which spaceborne and ground-based systems interoperate as components of a widely distributed supersystem. Without such an architecture, we risk simply converting a computing problem into a communications one, as often occurs with massively parallel architectures.

Hardware-fast and software-flexible

Implementing such an architecture and onboard data processing will require a phased approach. The field-programmable gate array (FPGA) is one technology that shows enormous potential for flexibly implementing high-performance data-processing systems. Conventional wisdom has long held that hardware is fast while software is flexible. The adaptive FPGA—an SRAM-based device that can be reconfigured during operation—offers the best of both worlds, enabling implementation of algorithms at the logic-gate level while retaining software's flexibility through the chip's reconfigurability. Such reconfigurability offers several advantages for space applications:

- new functionality can be implemented without the need to launch new spacecraft;
- the data collection or processing method can be changed interactively in real time, in response to the quality of the data received; and
- key algorithms can be altered in-flight to reflect changing conditions, advancing knowledge, or unanticipated anomalies.

We have already overcome bottleneck problems in ground-based processing by using computing techniques based on this technology. Using FPGA-based processing to accelerate the moderate imaging spectroradiometer (Modis) reflective calibration algorithm, and for multispectral image classification, showed an order-of-magnitude acceleration over

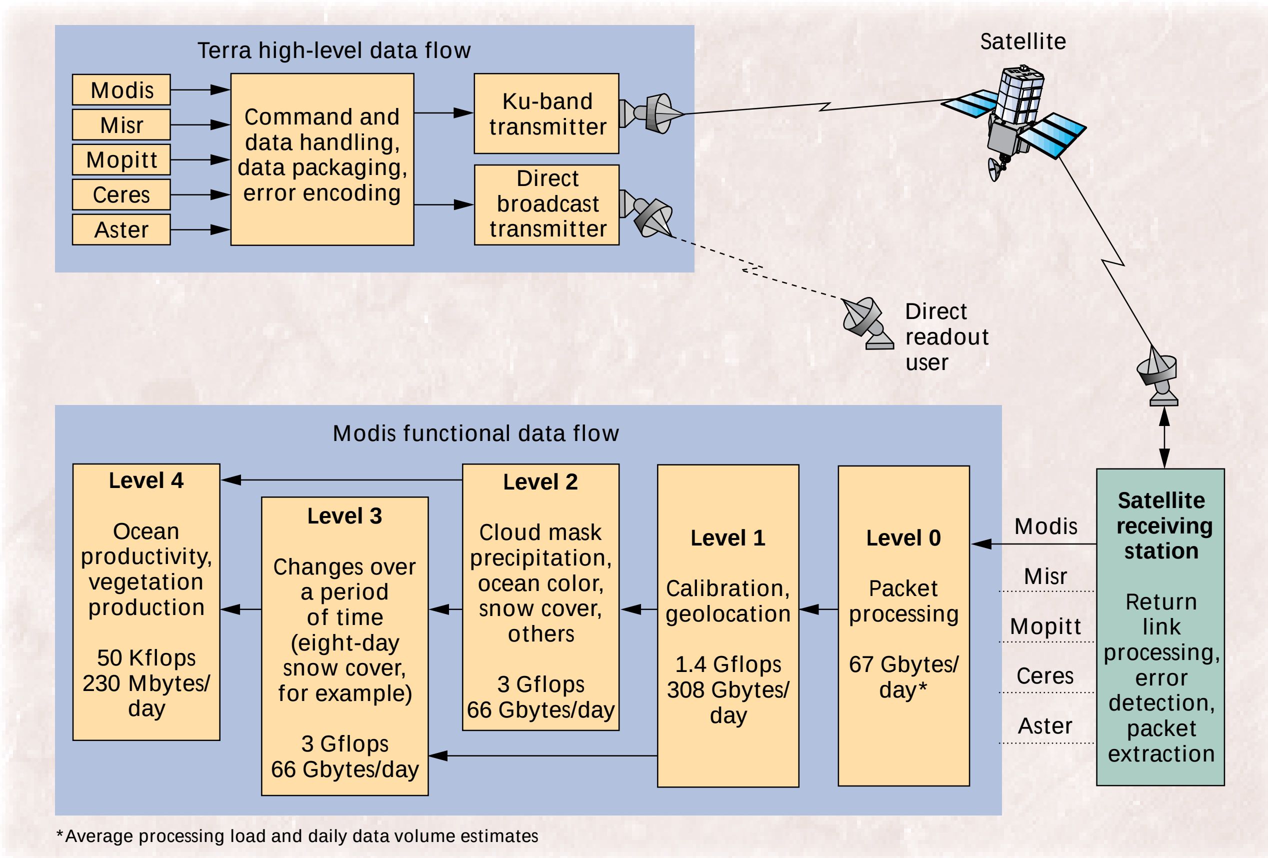


Figure 1. High-level representation of the Terra spacecraft and ground system functional data flow depicting the Modis instrument data processing functions. For each processing level, the diagram shows its respective average processing load and daily data volume estimates.

high-end workstations in both applications. (See http://fpga.gsfc.nasa.gov for more information about this work.) But these achievements provide only stopgap solutions to the demand for an ever-greater volume of faster, cheaper, and more flexible processing power.

Making the leap to space

Inevitably, adaptive computing techniques must migrate to the spacecraft itself to relieve the burden on ground-based systems. Adding the capability of preprocessing the data onboard, before transmission, will be, to use a fuel analogy, the equivalent of allowing spacecraft to transmit refined gasoline instead of crude oil. Yet spacecraft pose an inherently hostile environment that raises issues of power consumption, device reliability, thermal dissipation, and radiation-effects susceptibility. The adaptive FPGA will allow the migration of traditional, ground-data-processing functions from software to onboard reconfigurable hardware. For example, a spacecraft with an adaptive FPGA installed can receive a new configuration via uplink, hold one in internal memory until needed, or both.

This development will result in innovative architectures that combine spacecraft and ground systems in new relationships, off-loading many data processing tasks to the spacecraft. For example, it may well be possible within five to 10 years for NASA spacecraft to transmit scientific data directly to commercial satellites for distribution over the Internet.

A FIRST STEP

The first of NASA's spacecraft to significantly increase the data production rate will be the Earth Observation System AM-1. Recently renamed Terra, this spacecraft will provide data on atmospheric chemistry, hydrology, geophysics, climate change and trends, land use, and the state and trends of the global biosphere. Terra will generate more Earth observation data in its first six months of operation than NASA has collected since the organization's inception. In the Earth Observation System context, the ground-system data-processing functions span several levels:

- *level 0*—reconstructed, unprocessed data at full resolution from which all communications artifacts, such as error-correcting codes and framing, have been removed;
- *level 1*—level 0 data that has been time-referenced and annotated with ancillary information, including radiometric and geometric calibration coefficients and geolocation information;
- *level 2*—derived geophysical variables at the same resolution and location as level 1 data;
- *level 3*—variables mapped on uniform space-time grids, usually with some completeness and consistency; and
- *level 4*—model output or results from analyses of lower level data.

As Figure 1 shows, the Terra spacecraft contains an onboard instrument suite that consists of

- Modis, a moderate-resolution imaging spectroradiometer;
- Misr, a multiangle spectroradiometer;
- Mopitt, an instrument that measures pollution in the troposphere;

- Ceres, a clouds and earth radiant-energy system instrument; and
- Aster, an advanced spaceborne thermal emission and reflection radiometer.

Modis, one of five instruments onboard Terra, is a whisk-broom scanning and imaging radiometer that consists of a cross-track scan mirror, collecting optics, and a set of linear arrays with spectral interference filters located in four focal planes. Modis has a viewing swath of 2,330 km and will provide high-radiometric-resolution images of daylight-reflected solar radiation and day and night thermal emissions over all regions of the globe. Its spatial resolution ranges from 250 m to 1 km at nadir. The instrument's broad spectral coverage (0.4 to 14.4 μm) is divided into 36 bandwidths optimized for imaging specific surface and atmospheric features. Modis has a sustained data transfer rate of approximately 6.2 Mbps and can transmit 10.8 Mbps at peak output.

The calibration of the digital values produced by Modis to create significant radiance and emissivity values is a level 1 process. The estimated processing load required by the instrument calibration algorithms is 1.4 Gflops. The Adaptive Level One Accelerator we're developing now uses adaptive computing to process the Modis calibration algorithms. Aloa is a prototype that complements a Terra data-ingest system and delivers a visible image at the instrument scan data rate of 1.477 seconds. The Aloa will also serve as a pathfinder project for establishing spacecraft architectures that can deliver science products directly to the user.

When Terra deploys in July, the Aloa will be able to display Modis images in real time as the satellite crosses over a Terra receiving ground station. The system will also serve as a testbed for the insertion of level 2 and higher data products, using adaptive hardware resources to achieve real-time data production.

The supercomputing performance promised by adaptive hardware may finally enable the downlink of processed information, not just raw data.

Earth Observation System Data Product

By providing higher-resolution images, Terra's instruments will enable more accurate analyses than those provided by the current generation of spacecraft. Figure A shows an example of the kind of data products Terra will enhance. The chart shows the geographic distribution of the change, from 1982 to 1991, in the normalized difference vegetation index of land areas north of 27.75° N, expressed as the average over the northern active growing season of May through September.

The top panel shows the NDVI's percentage increase over 10 years, determined by linear regression of the year-to-year northern-growing-season's averaged NDVI. The middle panel shows the climatological NDVI of the active growing season. The bottom panel shows the change in spring temperature from 1982 to 1990, determined from average daily thermometer observations. You can see that springtime warming (shown in the bottom panel) over vegetated areas (shown in the middle panel) has caused increased plant growth in the northern high latitudes (shown in the top panel) during the 1980s.

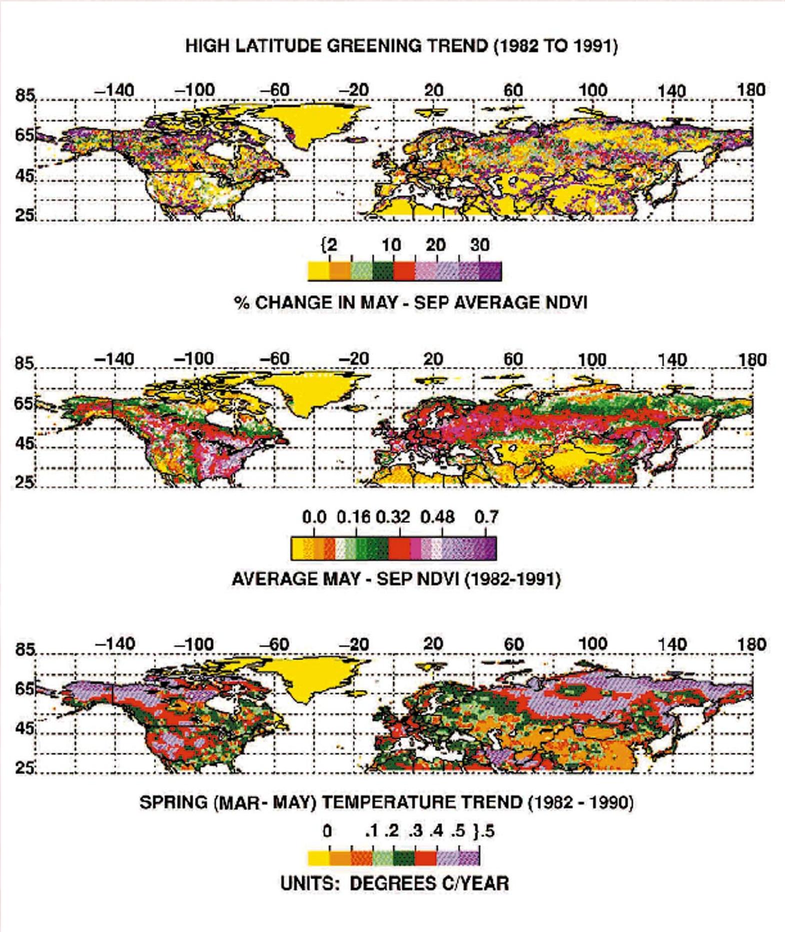


Figure A. Geographic distribution of the change in the normalized difference vegetation index (NDVI) of land areas north of 27.75° N, from 1982 to 1991, expressed as the average over the northern active growing season of May through September.

If it proves practical, this development will transform spacecraft into smart-instrumentation platforms. With the extension of data processing from ground-based installations to spacecraft, a diverse menu of new applications will become available.

At first, to prove the new technology, researchers will place experimental loads on spacecraft to process the data in parallel with the normal, raw-data download, so that the scientific value of the mission won't be lost if the new technology does not perform as expected. As spaceborne computing power becomes a reality, some missions will continue using it to complement even more powerful ground systems.

Other, less computation-intensive missions will find onboard data processing an acceptable solution for all their processing needs. In still other cases, a single spacecraft might produce relatively simple products for direct consumption while simultaneously downloading raw data for more complex analysis by ground-based facilities.

In all these applications, the ability to update the spacecraft's behavior on the fly will provide unprecedented flexibility. Much work remains, however, before this vision can become a reality. We face serious limitations in the current state of technology with regard to working in space and meeting the steep computational requirements of onboard information processing. Achieving our goals will require a cross-disciplinary engineering effort that must follow a yet-uncharted technology evolution. The Aloa project is our first step on that journey. ❖

Marco A. Figueiredo is an R&D engineer for SGT Inc.; Patrick H. Stakem is a professor of engineering science at Loyola College; Thomas P. Flatley is associate head, Ground Systems Hardware Branch, NASA Goddard Space Flight Center; and Tonjua M. Hines is a computer engineer at NASA GSFC. Contact Figueiredo at marco@fpga.gsfc.nasa.gov. For further information on EOS and Terra, see http://terra.nasa.gov.